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The slope-area method for estimating continuous discharge

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Cette publication hautement spécialisée La méthode d'estimation du déversement continu selon la méthode pente-section n'est disponible qu'en anglais en vertu du Règlement 411/97, qui en exempte l'application de la Loi sur les services en français. Pour obtenir de l'aide en français, veuillez communiquer avec le ministère des Richesses naturelles au informationarms@ontario.ca.

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Executive Summary

This report describes the background and underlying methodology to use the slope-area method to develop a continuous discharge time series at a remote site. It is intended as a method to employ at sites where time or logistical constraints preclude the development of a rating curve. Its utility is in the ability to obtain at least some information on the flow regime of an ungauged site that can aid decision making in the absence of any other streamflow information. The success of applying this method relies heavily on proper site selection, precise and accurate data collection, and the application of proper regression techniques.

Résumé

Ce rapport décrit le contexte et la méthodologie sous-jacente pour l'utilisation de la méthode pente-section en vue d'élaborer une série chronologique de déversement continu pour un site éloigné. Cette méthode devrait être employée dans des sites où des contraintes temporelles ou logistiques empêchent l'élaboration d'une courbe des débits jaugés. Son utilité réside dans la capacité d'obtenir au moins quelques données sur le régime d'écoulement d'un emplacement non jaugé pouvant contribuer à la prise de décisions en l'absence de toute autre information sur l'écoulement fluvial. Pour utiliser cette méthode avec succès, il est important de bien choisir le site, de recueillir les données de façon précise et exacte, et d'appliquer les bonnes techniques de régression.

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Introduction

A continuous record of streamflow discharge (historical and current) is important for assessing possible effects of a development on a stream or river ecosystem. However, many sites where this information is required are not located near an existing streamgauge. As a result, various methods that can be used to build a streamflow record to assess the hydrology of a site have to be explored. This usually involves establishing a monitoring station to collect data that can be used to estimate continuous streamflow, an endeavour sometimes faced with significant logistical constraints. The shorter streamflow record obtained at these monitoring stations can then be used in combination with hydrologic models or data from nearby streamgauges to extend the streamflow record and thus allow a more thorough characterisation of the flow regime for the site.

Most streamflow monitoring stations rely on an empirical relationship between the elevation of the water surface, commonly referred to as the stage, and discharge. This relationship is developed based on instantaneous pairs of stage and discharge measurements and is referred to as a rating curve (Figure 1).

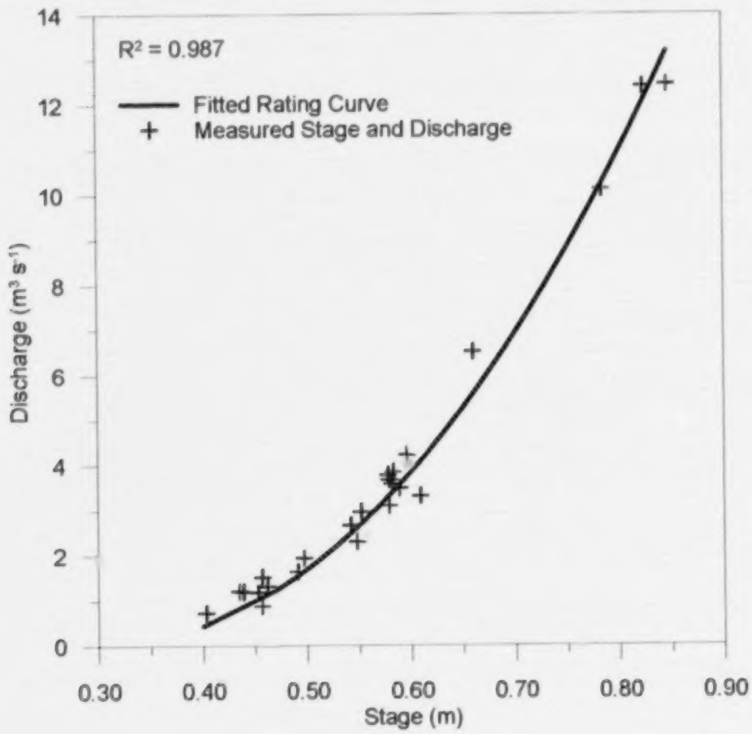


Figure 1: Typical shape of a rating curve.

Typically a rating curve requires at least 10 unique pairs of discharge-stage measurements to reduce the standard error in the relationship to an acceptable value (BC MOE, 2009; ISO, 2010). The paired discharge-stage measurements should also be spread over a wide range of flows and ideally include at least one discharge measurement corresponding to bankfull discharge. At least 10 visits to a gauging station are usually required to meet these conditions which is a significant commitment of time and resources, particularly for remote sites. This problem is exacerbated when a monitoring program must be established to provide information about streamflow at an ungauged site under tight time constraints. Under these conditions a different method may be required to develop a continuous record of discharge.

One such approach that has fewer data requirements is the slope-area method (Henderson 1966, Smith et al. 2010). This method, based on information related to the cross-sectional area, water surface slope and estimations of channel roughness, is most commonly used to estimate the peaks of extreme flood events when observed discharge

measurements are not available. These estimates are often made at ungauged sites but can also be employed at newly constructed streamflow monitoring sites to estimate high event flows for a rating curve until such flows are observed. The slope-area method can also be used to provide discharge estimates when it is deemed unsafe to collect direct measurements of discharge.

In recent years, the equipment used to monitor and measure water depth has become more feasible and simpler to operate, allowing for the rapid deployment of an accurate, cost effective system to measure water depth and water slope. This was demonstrated by Smith et al. (2010) who used the slope-area method to estimate continuous discharge of highflow events in small streams in arid regions where crest-stage gauges were traditionally used for the same purpose. In this document we extend the approach of Smith et al. (2010) by using the slope-area method for continuous monitoring of streamflow, not just highflow events. This application of the slope-area method is particularly advantageous when information about the hydrology of an ungauged site must be acquired as quickly as possible or to provide initial discharge estimates at remote sites until a sufficient number of discharge measurements can be acquired to employ traditional rating curve methods.

An estimate of the amount of effort to employ the rating curve and slope-area methods to provide continuous estimates of discharge is shown in Table 1. The actual level of effort depends, however, on the accuracy desired. In general, the range of error in individual discharge estimates using the slope-area method is 10–20% (Herschy 1985; cited in Dingman 2002). The range of error in individual discharge estimates using the rating curve method is typically in the range of 2-19% (McMillan et al. 2012) but highly dependent in individual errors associated with method used to measure discharge and rating curve development (Birgand et al. 2013; ISO 1997; McMillan et al. 2012).

Table 1: Estimated effort to apply the rating curve method to a site versus the slope-area method outlined in this report. Values in brackets ( ) indicate an absolute minimum requirement.

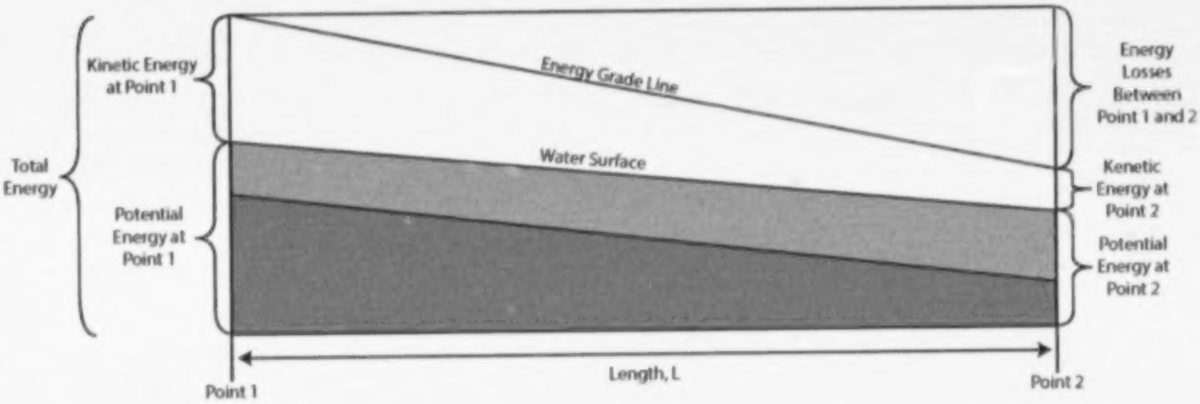
	Rating Curve	Slope-Area Method
Recommended number of discharge measurements	10+	2 to 4 (1 high; 1 low)[1]
Recommended number of site visits	10+	2 to 4
Recommended number of gauges	1	3 (2)
Recommended number of benchmarks	3 (1)	3 (1)
Estimated days required to establish a site	0.5 to 1	1
Estimated hours to conduct a site visit	3	3
Recommended number of cross-sections	1	3 (2)
Discharge measurements per site visit[2]	1	1

[1] Used to get direct estimates of Manning's n over a range of flows and therefore the more measurements acquired, the greater the accuracy of the estimates of discharge.

[2] Depends on equipment used (i.e. velocity meter vs. acoustic Doppler profiler) and the recommended number of cross-sections to minimise error in the discharge estimate.

The Slope-Area Method for Estimating Discharge

The slope-area method is an empirical approach to obtain an estimate of discharge using channel characteristics. In North America, and most of Europe, the Manning Equation has become synonymous with the slope-area method. The Manning Equation describes the relation between the sum of the potential and kinetic energy and the energy losses due to friction as water flows down a channel (Figure 2).



$$\text{Friction Slope (S)} = \frac{\text{Total Energy at Point 1 - Total Energy at Point 2}}{\text{L}}$$

Figure 2: Theoretical parameters relevant to the slope-area method. The total energy at Point 1 and Point 2 is equal to the sum of the kinetic and potential energies at each point.

As water flows from upstream to downstream there is a decrease in the total energy. The reduction in total energy is balanced by both frictional losses and gains in kinetic energy through increasing velocity. Frictional losses in a channel are mainly caused by channel bed friction, turbulent energy losses, and viscosity. The difference in total energy between two points is called the Energy Grade Line (EGL) and the slope of the EGL is called the friction slope, S.

The energy losses in a channel are approximated by a resistance factor called Manning's n. The value of n varies greatly depending on the bed material in a channel, the shape of the channel and the water velocity. In many cases the value of n is assumed to be constant for a channel but it can vary with water depth, the hydraulic radius, the diameter of bed material, and channel slope (Soong et al. 2012).

The Manning Equation, written in terms of discharge, is presented in Equation (1a):

$$Q = A\frac{S^{1/2} R_h^{2/3}}{n} \tag{1a}$$

where Q is the discharge of water in the channel ($m^3 s^{-1}$);
A is the cross-sectional area occupied by the flow (m^2);
S is the friction slope (m/m);
R_h is the hydraulic radius (m); and
n is a resistance coefficient, commonly referred to as Manning's n.

The hydraulic radius (R_h) accounts for the channel shape and how it influences the frictional losses and is calculated as:

$$R_h = \frac{A}{P_w} \tag{1b}$$

where A is the cross-sectional area occupied by the flow (m^2); and
P_w is the wetted perimeter (m).

Figure 3 demonstrates how to measure and calculate the wetted perimeter and hydraulic radius for a trapezoidal channel.

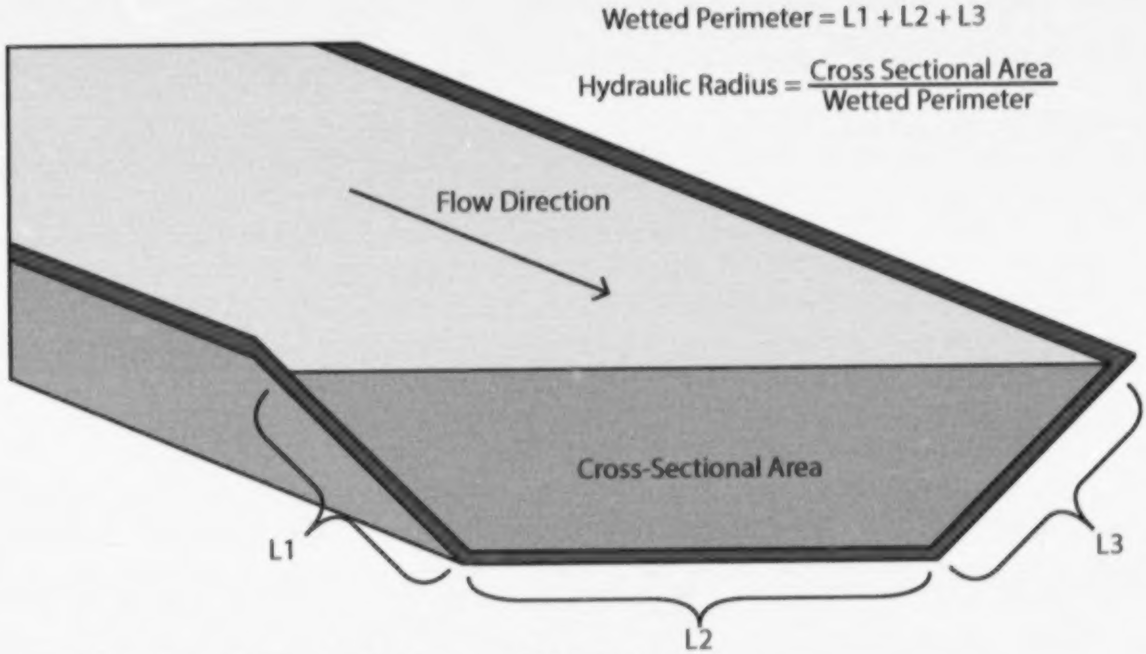


Figure 3: The calculation of hydraulic radius in a trapezoidal channel.

In many applications of the Manning Equation, either the channel bed slope or the water surface slope (S_w) is used to approximate the friction slope (S) (Figure 2). Channel bed slope is fairly representative of the friction slope in an ideal channel with uniform flow. However, in natural channels significant error is introduced by channel irregularities. Under these conditions S_w better approximates S because the value of S_w will change under different flow conditions and usually reflect the expected changes in S.

Another, and almost always larger, source of error comes from the value of n assigned to a channel. A comparison between the error in predicted discharge due to errors in assigned n as well as the assigned slope is presented in Figure 4.

The value of n can vary from 0.4 in extremely rough, turbulent mountainous streams consisting of large rocks and boulders to as low as 0.02 in smooth, meandering, sand bed channels (Chow 1959, Aldridge and Garret 1973, Barnes 1967, Henderson 1966, ISO 1070 1992). In most applications the value of n is estimated based on previous experience and expert opinion alone. However, in cases where discharge measurements and values for S_w, A and R_h are available, the value of n can be directly calculated using the Manning Equation, thus reducing the error associated with this term.

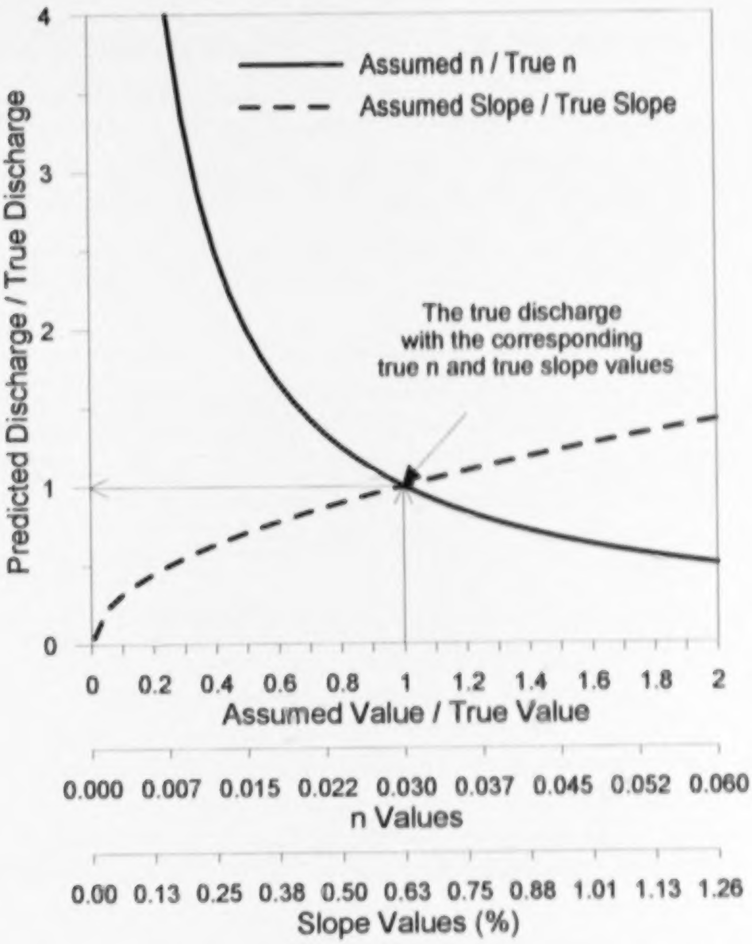


Figure 4: Comparison of the error in predicted discharge due to the error in the assigned *n* and slope given to a reach. Y-values indicate the relative difference between the predicted and true discharge for a given *n* or slope. A value of 1 indicates that the predicted and true discharges are the same and a y-axis value of 2 indicates the predicted discharge is two times larger than the true discharge.

Field Application of the Slope-Area Method

Overview

The continuous application of the slope-area method to a natural channel requires that all parameters in the Manning Equation either be continuously measured or estimated from continuous stage measurements. The success of applying this method is heavily reliant on the proper selection of the reach, installation of a set of at least three gauges to measure stage and water surface slope (S_w) (one upstream, downstream, and in the middle of the selected reach), proper cross channel surveys to provide values for P_w, A, and R_h, along with high quality discharge measurements that are used to calculate site specific n values.

Site Selection

The selection of an optimum reach to estimate a river's discharge is the first step to applying the slope-area method. The reach should have straight, well defined boundaries with a length and bed slope such that the elevation difference between the furthest upstream and downstream parts of the reach is greater than 10 times the

uncertainty of the instrumentation used to measure the water depth (ISO 1992). This means that if an instrument used to measure water depth has a measurement accuracy of ±0.02 m, the minimum vertical drop in the bed of a reach between an upstream and downstream gauge should be at least 0.2 m. A larger drop is required in reaches where the gauges are installed in highly turbulent areas in which case the minimum drop should be the 10 times the sum of the transducer accuracy and the amplitude of the waves.

There should be no sudden breaks in channel slope, large obstructions, sudden contractions or expansions along the reach, and a rapidly expanding channel must never be selected (ISO 1992). The flow must always be contained to a single channel and any reach that might be affected by backwater[1] should also be avoided. Practical considerations include sites that are accessible but not in high traffic areas where vandalism of instrumentation may be a concern. An example of a site where the slope-area method could be applied is shown in Figure 5.

In most cases not all of the criteria listed above can be met and therefore the best reach possible that minimises error in water depth and water slope measurements should be selected. Usually minor backwater effects can be accounted for through the use of a field measured variable *n* value but the relationship between *n* and stage will generally be more complicated.

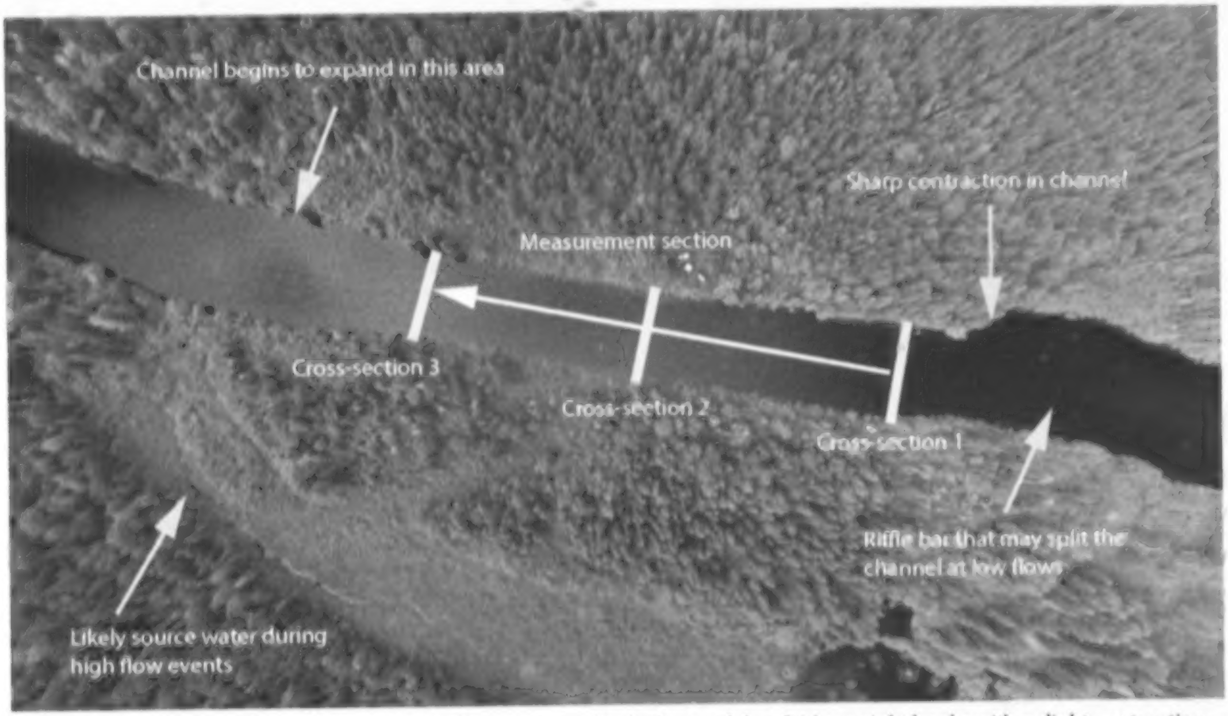


Figure 5: An example of a reach to apply the slope-area method. The reach has fairly straight banks with a slight contraction, all water is contained in a single channel and there are no signs of significant flow disturbance. There is an expanding section located downstream which may cause backwater effects during high flow periods. The entire gauging section should either be located upstream or downstream of the small creek highlighted in the bottom left of the photo. There must never be a source of additional discharge between two gauges.

Stage and Water Surface Slope Measurement

The water surface slope (S_w) of a reach is estimated by measuring the water surface elevation (stage) at several points along a reach, referred to as gauges (Figure 6). S_w is calculated by dividing the difference between stages measured at two gauges by the longitudinal distance between them (e.g. the upstream and downstream gauges). While only two gauges are required to calculate S_w in a reach, a minimum of three gauges are recommended to allow additional

1 Backwater effects refer to conditions where the water level in a channel is not controlled by local objects, such as rapids, bed friction or channel shape, but instead by downstream conditions. Backwater effects can be caused by trees, sudden decreases in slope, channel contractions and channel expansions

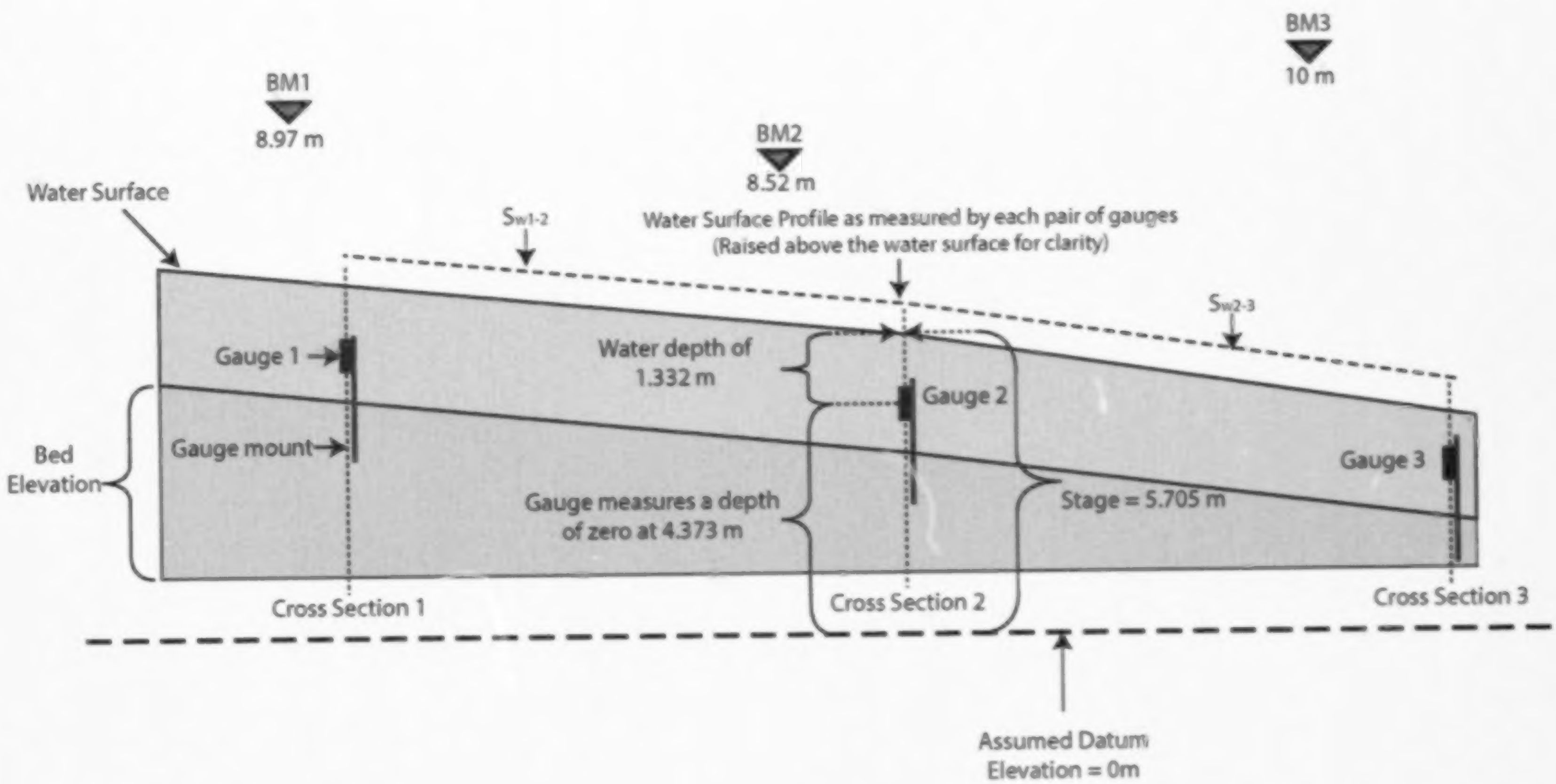


Figure 6: Typical longitudinal profile of a site where the slope-area method is applied. The two water surface slopes are denoted by S_{w1-2} and S_{w2-3} for the upstream and downstream slopes, respectively. Benchmarks 1, 2 and 3 are labelled BM1, BM2 and BM3 and their elevations are all relative to the assumed datum.

estimates of S_w (see Figure 6). With three gauges installed, at least two water surface slopes can be calculated between two adjacent gauges to check if S_w varies significantly over a range flow conditions and along the reach (i.e. S_{w1}, S_{w2}) and it also ensures at least one slope can be calculated if one gauge fails. Moreover, it permits the method to be applied at two of the cross-sections and therefore result in two discharge estimates (ie. cross-sections 2 and 3 using $S_{w1\,2}$ and $S_{w2\,3}$, respectively). These can be checked for consistency, averaged, and ultimately provide greater confidence in the result. At sites where the reach characteristics are complex or there is uncertainty in where to install the gauges, additional gauges may be required.

Gauge Installation and Operation

The proper selection of gauging locations along a reach is critical to accurate stage and slope measurement. Any noticeable inflection points in bed slope should be instrumented with a gauge to provide a better estimate of S_w along the reach. There should be no pools or large pieces of debris in the reach between any of the gauges and all gauges should be located as far upstream of channel disturbances as possible.

The horizontal position of a gauge in the channel cross-section is also very important. All gauges should be installed where there is minimal turbulence under all flow conditions. This means a gauge should not be directly located behind or in front of a large rock or tree which will directly influence stage measured at that point. Gauges must remain submerged under all expected flow conditions and should never become frozen during the winter months. The minimum expected water depth measured by a gauge should always be three times greater than the diameter of nearby bed material to minimize the chances that individual rocks or boulders affect the recorded stage values under low flow conditions.

Gauges must be mounted in stable, immobile material that will remain secure under any foreseeable flow conditions. If using a pressure transducer as a gauge (discussed in the following section) a piece of sharpened rebar driven ~1.2 m (4 feet) into the channel bed works fairly well. If the channel bed is formed of bedrock, a pressure transducer can be mounted at the end of a pipe which can be bolted directly to bedrock and extended out into the channel. Lastly, the measurements taken by a set of gauges must occur synchronously and they should all operate on the same time interval to ensure the measurements are comparable and S_w can be calculated accurately.

Gauge Instrumentation

There is a large variety of instrumentation available to measure and record the water level at a gauging site. One of the most economical and practical ways to continuously measure water depth in remote locations is to use non-vented pressure transducers (PTs). PTs are available from several manufactures and have a typical measurement accuracy of ±0.2 to ±0.5cm. They are extremely durable, and capable of measuring water depths up to 9 m on the most accurate models.

Non-vented PTs contain an internal data logger which allows them to be directly installed into a stream or river without the need to be connected to a data logger on shore. These PTs typically store a maximum of 20,000 to 120,000+ unique measurements depending on the manufacturer and data compression method used. This corresponds to a maximum deployment time between 60 and 400 days, respectively, using a 5 minute interval to log water depth. The sampling rate of a PT is also fully customizable.

Many manufactures also produce data cables that can be attached to submerged, non-vented PTs allowing data to be downloaded from the channel bank without having to enter the water or remove a PT from its mount. These cables are highly recommended for all gauging sites since fluctuating stream flow and colder water temperatures sometimes make it difficult to safely retrieve non-vented PTs for downloading.

Establishment of a Site Datum and Benchmarks

Once the gauges are installed in a reach, a site datum must be established along with a set of benchmarks. Gauges can only measure the depth of water above them and therefore the water depths measured by a gauge must be converted to stage to make data comparable between gauges. Stage is defined as the elevation of the water surface at a gauging point relative to a site datum (Figure 6).

The vertical position of a gauge is measured relative to a datum (an arbitrary plane that is assigned an elevation of zero) using a set of benchmarks. A benchmark is a defined point of known elevation and position that does not change in time. All elevations measured at a site are taken relative to a set of benchmarks, and these elevations are then converted to an elevation relative to the site datum. To calculate the stage, the measured water depth at a gauge is added to the gauges elevation. This process, along with an example site layout, is highlighted in Figure 6. In this figure, the assumed site datum is located 10 m below Benchmark 3 (BM3). To calculate the elevation of any other point at a site, the difference in elevations between BM3 and the point of interest are added together. For example, if BM2 is located 1.48 m below BM3, BM2's elevation is equal to 10 m plus -1.48 m, or 8.52 m above the site datum. Similarly if BM1 is located 1.03 m below BM3, it would have an elevation of 8.97 m.

At least three benchmarks should be installed at a site to ensure that the location of the site datum remains constant (Handkamer 1999). At least one benchmark must be installed in permanent, immobile material, such as a lag bolt drilled into a large rock or bedrock outcrop or a piece of rebar driven into the ground below the frost line (Handkamer 1999; Rantz et al. 1982). If this is not possible, a spike driven into a tree is also acceptable, but not ideal. A total of three benchmarks is strongly recommended to detect any shifts in the established benchmarks and to provide redundancy in the case that one of the benchmarks is somehow lost or destroyed (Rantz et al. 1982). The assigned location of the site datum must be below the lowest point in the channel bed in the measurement reach. This is done to eliminate the possibility of measuring negative stage values which will result in unnecessary complications and confusion when processing stage data collected from the gauges.

Once the site datum and benchmarks have been established, it is good practice to survey the water surface elevation at each gauge each time the site is visited. The surveyed water level should be compared to measured values at each gauging location to ensure the instrumentation is accurate. All comparisons between gauge measured and surveyed water levels should be recorded and any difference between the two values noted clearly in these records. The time when stage is surveyed should correspond to the exact time the gauge of interest records a measurement. For instance, if a pressure transducer is recording instantaneous measurements on a 15 minute interval starting at 12:00, the water surface should be surveyed at 12:15, 12:30, 12:45, and so forth.

Cross-Sectional Area and Hydraulic Radius

The cross-sectional area (A) and hydraulic radius (R_h) for all stages measured at a gauging cross-section site can be calculated directly from a cross-sectional survey of the channel. A cross-sectional survey is performed by stretching a tag line across a channel and measuring channel bed elevation in small increments along the cross-section using a level and survey rod. If a reach is not wadeable under even the lowest of flow conditions, specialized bathymetric measuring equipment may be required. Cross-sectional surveys should be taken at gauge stations 2 and 3 (see Figure 6) to allow discharge to be calculated at both of these locations. It is good practice to repeat cross-sectional surveys on an annual basis to detect any changes in channel characteristics that may influence the discharge calculated using the slope-area method.

Field Measurements of Discharge

Since there are no significant inputs/outputs along the selected reaches (or through the bed and banks) it can be assumed that the discharge passing through all cross-sections is equal. Thus, field measurement of discharge is only required at one of the cross-sections in the reach. A minimum of two discharge measurements are required each time a site is visited. If time permits, additional measurements can be made to reduce error in the discharge estimate. There should not be large differences between each discharge measurement. Accepted standards for discharge measurement can be found in CAN/CGSB (1991), Lane (1999), and Rantz et al. (1982). If working on a non-wadeable river where an acoustic Doppler current profiler (ADCP) is used, standardized methods can be found in ISO/TS (2005).

Data Analyses

Relation between Stage, R_h and A

From the survey data collected at cross-sections 2 and 3 the relationships between stage, A, and R_h can be directly calculated. These relationships can then be used to estimate A and R_h for any stage and to calculate n in Equation (2) and discharge in Equation (1a).

Manning's n

With field measurements of discharge (Q), synchronous measurements for S_{w1-2}, S_{w2-3} and stage, along with A and R_h calculated using the stage, Equation (1a) can be rearranged to directly solve for Manning's n:

$$n = A\,\frac{S^{1/2} R_h^{2/3}}{Q} \qquad (2)$$

As mentioned above, n values should be calculated using S_{w1-2}, S_{w2-3} at cross-section 2 and cross-section 3, respectively (Figure 6). This allows two discharges to be calculated and averaged when applying the Manning Equation to generate a continuous hydrograph. Because this method utilizes the water surface slope to calculate discharge rather than the friction slope along a reach, the value of n becomes a catch-all term for all energy losses (Anderson 1999). Many of the additional energy losses are strong functions of stage, which in turn means n tends to be a function of stage as well.

Stage and n Relationship

Once several sets of stage and discharge pairs are collected for a site, a relation between n and stage for the two cross-sections can be developed. Approximately three to five sets of discharge-stage measurements are recommended. Whenever possible, additional discharge-stage measurements should be taken as a larger number of data points will increase the confidence in the relationship.

For most natural channels, the value of n will usually decrease with an increasing stage up to the bankfull flow. This trend is caused by a decreasing ratio between the size of the bed material and the depth of flow which results in a smaller fraction of the flow being in contact with the channel bed, which in turn diminishes the relative influence of bed friction on the flow rate.

Conversely, the value of n will increase once flows enter riparian areas. Thus, the derived n-stage relationship is not applicable when the water level in the channel overtops the main banks and begins flowing into the riparian zone unless a direct discharge measurement is taken at the corresponding stages. Under these conditions the method outlined in ISO (1992) should be followed. This method divides the channel into separate sections and uses tabulated values of n which are selected depending on the presence and type of vegetation. The slope recorded by the gauging stations should still be used in these cases as it should provide a more accurate estimate of the water slope than reading the water slope left by the debris line.

Increasing values of n with increasing stage at discharges corresponding to flows below bankfull may indicate that one or more of the gauges is being affected by backwater influences. Under these circumstances it is very difficult to provide a recommendation of what values of n are valid or how to use a correlation between discharge and stage. The most conservative approach is to only apply observed n values to stages beyond those used to calculate the n-stage relationship, which may lead to an overestimate of Q (all other things being equal).

The relation between n and stage, along with the relative magnitude of n will be governed by specific site conditions. Streams in southern Ontario have n values reported between 0.1 and 0.011 depending on stream roughness, flow depth and the bed material (Annable 1996). Keep in mind that the range of n reported by Annable (1996) is for rivers in southern Ontario only. Rivers located in northern Ontario can be very different and consist of a variety of bed materials, from sand to gravel to bedrock, and the slopes and turbulence of such rivers may also be much higher. A good and very detailed reference, complete with pictures and cross-sectional survey data along with calculated n values from a set of 50 rivers located across the USA, can be found in Barnes (1967).

Stage and Slope Relationship

There may be times when an empirical relationship between S_w and stage at a selected gauge is required due to the failure of equipment or the loss of another gauge. Under these circumstances a relationship between Sw and stage may be developed, provided the stage and S_w covers a range of flows between a low flow period and at least bank full discharge. A relationship between S_w and the stage measured by a single gauge may then be used to provide ongoing estimates of S_w to be used in Equation (1a) and thereby allow the additional gauges in a reach to be removed.

Caution should be exercised when using a regression equation to estimate values of S_w for corresponding stage values beyond those that have not been previously observed at the site. Slopes corresponding to riparian flows should never be estimated unless previous slope-stage data are available. If required, an estimate of S_w during the peak discharge of a riparian flow can be estimated by examining the slope of the debris line left behind when the flow recedes, following the procedures outlined in Rantz et al. (1982) or ISO (1992). The use of the debris line is only required when S_w cannot be estimated for a peak event using gauged data.

While it may be attractive to use a single gauge and the slope-stage relationship to estimate S_w, it is not recommended under most circumstances as it introduces unnecessary uncertainty into the discharge measurements. By keeping all gauges active, the estimates of S_w are always based on measured values, allowing changes in channel shape to be detected and perhaps indicating when new *n* values need to be derived. Given the relatively low cost of PTs it is recommended that all three gauges remain in situ to maintain confidence in the discharge estimates using the slope-area method.

Continuous Discharge Estimates Using the Manning Equation

Using the measured slope and stage data and the established relationships between *A* and stage, R_h and stage, and *n* stage, a continuous discharge record can be calculated using Equation (1a) at the time interval for which stage is recorded (i.e. 15 min., 30 min., 60 min. with an interval of 15 min. being recommended). Again, the discharge should be calculated using a minimum of two sets of water surface slope data and two different gauged cross-sections (i.e. S_{w1} and cross-section 2, S_{w2} and cross-section 3). There should be minimal differences between the discharges predicted at the two cross-sections. Depending on how the discharge data are to be used, the discharge estimates may be averaged or can be presented together to show the variability in the estimates.

The Slope-Area Method Discharge Calculator (SAMDC) is a stand-alone software tool that can be used to complete the data analyses described in this Section to estimate continuous discharge at a site. The software is freely available and can be downloaded at: http://people.trentu.ca/rmetcalfe/SAMDC.html.

Stage and Discharge Relationship

The continuous estimation of discharge using the Manning Equation along with the continuous measurement of stage at a gauge allows for the creation of a discharge-stage plot which may be useful when examining environmental characteristics of a stream or river. Any direct discharge measurements taken at the site should also be plotted and noted clearly on the discharge-stage plot. A discharge-stage plot created using discharge values calculated with the slope-area method should not be referred to as a rating curve. The name rating curve implies the relationship between stage discharge data derived using a set of discharge-stage measurements rather than the slope-area method. A discharge-stage relationship is calculated by plotting the stage data from one gauge along the reach against the corresponding averaged discharge data (i.e. an average of the corresponding discharge measurements estimated at each cross-section using the Manning Equation). A curve may then be fitted to this plot and the resulting equation may be used to predict discharge based on any reasonable stage value. There is considerable choice in what curve to fit to the data but in most cases a power function will provide the best fit (i.e. $y = a(x)^b$ or Discharge = $a(\text{Stage})^b$). For many hydrology applications, the standard discharge-stage relationship is assumed to take the form of Equation (3) (Rantz et al. 1982):

$$Q = a(Stage - PZF)^b \quad (3)$$

where Q is the discharge of water in the channel ($m^3 s^{-1}$);
a is a coefficient;
Stage is the stage measured at a gauge (m);
PZF is the point of zero flow (m); and
b is an exponent.

The presentation of Equation (3) in this document does not constitute or imply the requirement to use it. Rather it is presented as a possible method to fit a curve to the discharge-stage data collected at a site. If the site where this method is applied becomes a permanent monitoring station, the discharge-stage curve can be converted to a rating curve (cf. ISO, 2010 or Rantz et al. 1982).

Data Quality

The single most important aspect of applying the slope-area method is the collection of high quality data and ensuring all data are screened for errors before they are used to calculate discharge. A minimum of two discharge measurements are recommended each time a site is visited and more if there are large differences between each discharge measurement.

When examining stage data, there should be no sudden or sharp shifts in the recorded stages. Spikes in stage data may indicate debris caught in the channel, an ice jam if the spike occurred during the winter months, or that the gauge has shifted on its mount. During each site visit the stage at each gauge should be surveyed and compared to the stage values recorded by the gauge. The values measured in the survey and by the gauge should be recorded and well documented to maintain a record of the accuracy of the gauging station and can be used to detect any small changes or drifts in the sensors if they occur. This step is crucial, as a small error in stage measurement may have a large effect on the discharge estimated using the Manning Equation, especially under low flow conditions.

All stage values recorded by all gauges must occur synchronously. During each site visit, the internal clock of each gauge must be synchronised with the clock on the field computer used to download the data. The time between site visits should be no longer than the time it takes for a gauge to run out of memory. It is strongly recommended that gauges are never adjusted for daylight savings time as can lead to confusion later on when the data are interpreted.

Summary

The following is a brief step-by-step summary of the methods presented in this document:

1. **Select a straight river reach** with stable beds and banks, no sudden breaks in slope or large obstructions, contractions, expansions or inputs and outputs of water along the reach (i.e. tributaries and groundwater) and with a minimum elevation difference of 10 times the uncertainty of the instrumentation used to measure water depth.

2. **Select three cross section locations** within the reach and install one pressure transducer at each to continuously monitor flow depth. Pressure transducers should be located deep enough in a channel to remain submerged under all flow conditions.

3. **Conduct a site survey** to obtain cross section geometry at the three cross section locations, the location and elevation of the pressure transducers and the longitudinal slope of the reach. This will provide the necessary field data to convert the water level data to a common stage, determine the cross-sectional area and hydraulic radius, and to estimate Sw.

4. **Determine the relationships between A vs. stage and R_h vs. stage** for cross-sections 2 and 3 using the survey data.

5. **Obtain discharge measurements** at different stages (two or more measurements for each visit, then averaged) to estimate Manning's *n*, relate Manning's *n* to stage, relate slope (S_w) to stage, and discharge to stage for cross-sections 2 and 3.

6. **Estimate discharge** at the various measured intervals using Manning's equation and the continuous stage measurements and associated slope (S_w), hydraulic radius (R_h) and n values.

7. **Maintain site** by making annual or semi-annual site visits to download data from pressure transducers and check for changes in the reach that may affect the value of n or influence the measured slope. After large flood events, all cross sections should be resurveyed to account for possible changes due to deposition or removal of sediment.

References

Aldridge, B. and Garret, J. 1973. Roughness Coefficients for Stream Channels in Arizona. USGS Open-File Report: 73-3, 87 p.

Annable, W. 1996. Morphologic Relationships of Rural Watercourses in Southern Ontario and Selected Field Methods in Fluvial Geomorphology. Ontario Ministry of Natural Resources. 85 p.

Anderson, J. 1999. Water Survey of Canada: Hydrometric Technician Career Development Program: Lesson Package No. 18 – Stage Discharge Relation. 19 p.

Barnes, J. 1967. Roughness Characteristics of Natural Channels, USGS Water Supply Paper 1849. 25 p.

Birgand, F. Lellouche, G. and Appelboom, T.W. 2013. Measuring flow in non-ideal conditions for short-term projects: Uncertainties associated with the use of discharge-stage rating curves. J. Hydrol 503: 186-195.

BCMOE, 2009. Manual of British Columbia Hydrometric Standards. 203 p.

CAN/CGSB-157.2. 1991. Liquid Flow Measurement in Open Channels Velocity-Area Methods. 23 p.

Chow, V.T.1959. Open-Channel Hydraulics. McGraw-Hill, New York. 680 p.

Dingman, S.L. 2002. Physical Hydrology 2nd Edition. Waveland Press Inc., Il. 646 p.

Handkamer, C. 1999. Water Survey of Canada: Hydrometric Technician Career Development Program; Lesson Package No. 3 – Bench Marks and Gauge Datum. 24 p.

Henderson, F. 1966. Open Channel Flow. Macmillan Publishing, New York City. 552 p.

Herschy, R.W. 1985. Streamflow Measurement. New York, NY: Elsevier Applied Science Publishers. 524 p.

McMillan, H. Krueger, T. and Freer, J. 2012. Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. Hydrol. Process. 26: 4078-4111.

ISO, 1997. Measurement of Liquid flow in open channels – Velocity-area methods. International Standards Organisation Publication 748, Geneva, Switzerland. 46 p.

ISO/TS 24153. 2005. Hydrometry – Measuring river velocity and discharge with acoustic Doppler profilers. International Standards Organisation, Geneva, Switzerland. 45 p.

ISO 1992. Liquid Flow Measurement in Open Channels – Slope-Area Method. International Standards Organisation Publication 1070, Geneva, Switzerland. 12 p.

ISO 2010. Measurement of Liquid Flow in open channels, Part 2: Determination of the discharge-stage relationship. International Standards Organisation Publication 1100-2, Geneva, Switzerland. 28 p.

Lane, R. 1999. Water Survey of Canada: Hydrometric Technician Career Development Program; Lesson Packages No. 10.1, 10.2, 10.3 – Principles of Discharge Measurement. 60 p.

Rantz, S. and others. 1982. Measurement and Computation of Streamflow. USGS Water Supply Paper 2175. 603 p.

Smith, C., Cordova, J. and Wiele, S. 2010. The Continuous Slope-Area Method for Computing Event Hydrographs, U.S. Geological Scientific Investigations Report 2010-5241. 37 p.

Soong, D., Prater, C., Halfer, T. and Wobig, L. 2012. Manning's Roughness Coefficients for Illinois Streams, U.S. Geological Survey Data Series 668. 14 p.

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